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High burn-up spent nuclear fuel transport reliability investigation[☆]

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ABSTRACT

Transportation packages for spent nuclear fuel (SNF) must meet safety requirements under normal and accident conditions as specified by federal regulations. During road or rail transportation, SNF will experience unique conditions that could affect the structural integrity of the cladding due to vibrational and impact loading. Lack of SNF inertia-induced dynamic fatigue data, especially for the high burn-up (HBU) SNF systems, has brought significant challenges to quantify the reliability of SNF during transportation with a high degree of confidence. To address this shortcoming, Oak Ridge National Laboratory (ORNL) developed a SNF vibration testing protocol without fuel pellets removal, which has provided significant insight regarding the dynamics of mechanical interactions between pellet and cladding. This research has provided a detailed understanding about the effect of loading rate and loading mode on the fatigue damage evolution of HBU SNF under normal conditions of transport (NCT). Static and dynamic loading experimental data were generated for SNF under simulated transportation environments using a cyclic integrated reversible-bending fatigue tester (CIRFT), an enabling hot-cell testing technology developed at ORNL. SNF flexural tensile strength and fatigue S-N data from pressurized water reactors (PWRs) and boiling water reactor (BWR) HBU SNF are presented in this paper, including the potential effects of pellet-cladding interface bonding, hydride reorientation, and thermal annealing to SNF vibration reliability. These data can be used to meet the nuclear industry and U.S. Nuclear Regulatory Commission needs in safety of SNF transportation operations.

1. Introduction

Spent nuclear fuel (SNF) transportation has long been established as an important part of the backend of the industrial nuclear fuel cycle. An important factor to be taken into account is the current trend toward higher burn-up (HBU), which is driven mainly by economic reasons in the competitive power market. Transportation packages for SNF must meet safety requirements specified by federal regulations (NRC, 2010). For normal conditions of transport (NCT), vibration loads incident to transport must be considered; this is particularly relevant for HBU fuel (>45 GWd/MTU) due to changes in cladding properties induced by HBU conditions. Besides the structural changes in both fuel pellets and cladding that occurs during irradiation, the SNF rods typically have burnup induced damage (pores and micro cracks), oxide and hydride layers, residual stresses, altered interfaces, and trapped fission products. Understanding the impact of these changes may have on the strength of the SNF fuel/cladding system is required to accurately simulate the performance of SNF rods during transport. Transient shock and steady vibrations can impose substantial loading to SNF rods resulting in mechanical fatigue. The fatigue is exacerbated in the case of HBU SNF, due to increases in cladding corrosion layer thickness, cladding hydrogen content, cladding creep deformation, fission gas release, fuel pellet swelling and formation of a HBU structure at the surface of the fuel pellets. As a result, the HBU SNF rods are susceptible to premature failure; therefore, their mechanical behavior must be carefully understood and controlled to satisfy the regulatory requirements.

The mechanical properties of HBU defueled cladding have been previously studied by subjecting defueled cladding tubes to longitudinal (axial) tensile, ring-stretch, ring-compression, and biaxial tube burst tests (Geelhood et al., 2008). To understand the fatigue properties of cladding materials used in the reactor core, the cyclic fatigue of Zircaloy was studied under various loading conditions including tension and bending (O'Donnell and Langer, 1964; Pettersson, 1975; Nakatsuka

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et al., 1991). In a later study (Wisner et al., 1994), it was shown that irradiation reduces the fatigue life of all materials in the low cycle regime. However, in these experimental efforts, fuel cladding was studied as a stand-alone material with no fuel pellets included. This is significant because the pellet-cladding mechanical interaction (PCMI) affects the mechanical response of fuel rods as demonstrated in analyses of reactivity-initiated accidents (RIA) (Fuketa et al., 2001); (Tomiyasu et al., 2007) . Furthermore, the effect of the PCMI on the bending of fuel rods in a transportation environment is unclear. Moreover, stress state is further complicated by the stress gradient over the cross section in a SNF composite rod structure comprised of cladding and fuel pellets and their interfaces. Therefore, the understanding of bending response of SNF cladding under such a complex stress state is critical, especially considering the high stress-state sensitivity and anisotropy of mechanical property of cladding materials such as SRA Zry-4 (Link et al., 1998; Le Saux et al., 2010).

The objective of this research is to investigate the mechanical properties and behavior of SNF cladding with the embedded fuel pellets (including inertia induced PCMI) under vibration/cyclic loads similar to the sustained vibration loads experienced during normal transport (Wang et al., 2017). During the program development, the use of surrogate nuclear fuel rods has also been explored to investigate the mechanical responses of SRA Zry-4 cladding with aluminum oxide (alumina) pellets in which the PCMI is simulated by the interfaces between alumina pellets and Zry-4 cladding. The advantage of using surrogate rods is that testing parameters and testing materials are more controllable than tests using actual structures, which would need to be performed inside a hot cell as demonstrated in the recent activities at ORNL (Wang et al., 2012; Wang et al., 2013a,b; Wang et al., 2014a).

1.1. Status of the CIRFT testing program development

Since the CIRFT was commissioned in a hot-cell in 2013, we have used this instrument to collect experimental data on SNF from pressurized water reactors (PWRs), including H. B. Robinson (HBR) Zircaloy-4 cladding, North Anna (NA) and Catawba M5 cladding, and the Limerick Generating Station (LMK) boiling water reactor (BWR) under simulated transportation environments (Wang et al., 2014b–d). Testing on SNF rods from PWRs—HBR Zircaloy-4 cladding, NA and Catawba M5 cladding —demonstrated that the cyclic fatigue lifetime of SNF rods generally depends on the amplitude of the applied moment. It was also demonstrated that the lifetime of a SNF system is related to the degree of damage in the cladding and fuel pellets resulting from irradiation after a long term of service inside a reactor, as well as the loading amplitude and loading rate, due to different fatigue damage mechanisms triggered by the intensity of pellet-clad mechanical interaction. In 2015 CIRFT study further extended the vibration data collected to include LMK Zircaloy-2 data from a BWR environment, where all the tested LMK rods are coming from the bottom portion of the parent SNF rods. An S—N trend similar to that of the PWR data was also observed in the BWR data (Wang et al., 2015). Furthermore, the accumulated damage from the combination of low-amplitude CIRFT cyclic bending plus transient shocks (high-rate bending load) indicated an accelerated aging effect compared to that of low-amplitude cyclic bend loading alone. In 2016 CIRFT testing was extended to SNF hydride reorientation effect and annealing effect study; the HBU HBR CIRFT data was published in NUREG/CR-7198/R1 (Wang et al., 2017).

2. SNF system dynamic loading potential under NCT

The PWR fuel assembly skeleton (Adkins et al., 2013), as shown in Fig. 1, is formed by control rods' guide tubes and spacer grids designed to constrain fuel rods during a reactor operation. In a vertical service setup, the skeleton is subjected to vibration loads induced by fluid dynamics, and the rods' dead weight is transmitted through the spacer grids to the guide tubes during reactor operation. When the SNF assembly is in a horizontal orientation under NCT, the skeleton formed by the guide tubes and spacer grids becomes the primary load-bearing system that carries and transfers the inertia-induced vibration loads within an SNF assembly. This includes interaction of forces between the SNF assembly and the canister basket walls as illustrated in Fig. 1.

Random vibration registered at the SNF transport cask, which is excited from the truck or railcar bed, provides the external loading driver to vibrate the SNF assembly. In addition to this external vibration driver, the fuel assembly also registers internal transient shocks resulting from the dynamic interactions among the fuel assembly components inside the cask. These components include the skeleton, fuel rods, and canister basket walls. Their dynamic interactions can significantly increase the high-rate impact loading intensity and frequency within fuel assembly components during NCT. Sandia National Laboratories (SNL) registered maximum 22 g peak vertical vibration acceleration at mid span of the surrogate rod adjacent to the spacer grid from the accelerometer reading during the truck transportation test (McConnell et al., 2014). In contrast, the maximum vertical acceleration of 5.6 g was registered on the top of transport basket at mid-span.

In an Electric Power Research Institute (EPRI) Synthesis Report-1015048 (Rashid and Transportation, 2007), the plastic collapse of the spacer grids and the breakage of the guide tubes were considered as the two failure modes for evaluating fuel assembly damage. Therefore, the integrity of guide tubes and spacer grids during transport requires full attention since it will affect the dynamic load transmitting mechanism within the fuel assembly and will consequently dictate the multipurpose canister design concept to ensure safe SNF transport. Furthermore, the aged or fatigued skeleton has the potential to increase the interface gaps within the fuel assembly system. The consequence of increased gap potential is the increase in contact impact loading intensity and frequency between the fuel rods, the skeleton, and the basket wall. Thus, external cask vibration needs to be mitigated, along with internal dynamic amplification from the fuel assembly system vibration and its contact-interaction transient shocks (Wang et al., 2015). System damping of the transport cask may need to be increased to reduce SNF system vibration intensity. Such mitigations will eventually impact the design of the canister system.

Bending is a prevailing loading mode for SNF rods in both the hypothetical accident drop and NCT (Sanders et al., 1992). The magnitude of vibration depends on the road condition and the dynamics of the vehicle system, including transport cask design. The possibility of fuel release in the scenarios mentioned above relies on the capability of the fuel rod cladding to withstand the dynamic loading to contain the SNF. The vibration loads experienced by SNF rods during transportation can be characterized by dynamic, cyclic, and bending loads. The transient vibration signals in a specified transport environment can be analyzed, and frequency, amplitude and phase components of the vibration can be identified. The methodology developed at ORNL is a novel approach to support the study of the vibration integrity of actual SNF rod segments through the testing and evaluation of the fatigue performance of SNF rods at the targeted loads, including normal vibration loads as well as SNF system contact interactions induced transient shocks. ORNL has developed the CIRFT, shown in Fig. 2, to evaluate the response of the SNF rods under normal vibration loads as noted in Refs (Wang et al., 2017; Wang et al., 2012; Wang et al., 2013a,b,c; Wang et al., 2011; Wang et al., 2014e). A three-point deflection measurement technique using linear variable differential transformers (LVDTs) is used to characterize the real-time SNF rod's curvature under test conditions, and electromagnetic force linear motors are used as the driving system to provide the mechanical load. ORNL has used the test system in a hot cell since October 2013 to perform static and dynamic testing on HBU SNF to evaluate the flexural strength and the fuel–clad structure bending fatigue performance. The schematic diagram to illustrate how to use CIRFT test to assist the SNF effective lifetime evaluation under NCT is shown in Fig. 3. Fig. 3 shows that under Fast Fourier Transformation, the random vibration time-history wave forms can be